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Spacecraft Contamination Control Challenges for Space Missions with Organic Compound Detection Capabilities and for Potential Sample Return

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Abstract

Spacecraft contamination control is critical to space exploration missions with organic compound detection capabilities, and also for missions targeting acquisition of samples for potential return to Earth. Significant challenges are being addressed and resolved in the design of current flight projects and conceptual mission studies at JPL. These challenges extend to both orbiting spacecraft, as well as landed missions, for future missions to Mars and Europa, and potential missions to Titan and Enceladus.

Contamination control during all phases of a mission, from preliminary design through operation, is fundamental to ensure that organic compounds of terrestrial origin are controlled to ensure successful completion of science objectives.

This paper examines contamination control challenges specific to landed missions (which include sample acquisition, encapsulation, caching, potential sample return, and UV instruments), and orbiting missions (modeling interactions between the spacecraft and local exospheres and plumes).
Keywords: contamination, outgassing, spacecraft

Acronyms/Abbreviations

ACA	Adaptive Caching Assembly
CQCM	Cryogenic Quartz Crystal Microbalance
CVCM	Collected Volatile Condensable Materials
DUV	Deep Ultraviolet
LSE	Low Surface Energy
LSR	Low Surface Roughness
QCM	Quartz Crystal Microbalance
TiN	Titanium Nitride
TML	Total Mass Loss
TQCM	Thermo-electric Quartz Crystal Microbalance
UV	Ultraviolet [radiation]
UV-Vis	Ultraviolet–visible spectroscopy

1. Introduction

Contamination control is critical to space exploration missions with organic compound detection capabilities, and also for missions targeting acquisition of samples for potential return to Earth. Significant challenges are being addressed in the design of current flight projects and conceptual mission studies at JPL. These challenges extend to both orbiting spacecraft, as well as landed missions, for future missions to Mars (Mars 2020) and Europa (Europa Clipper), and potential missions to Titan and Enceladus.

Contamination control during all phases of a mission, from preliminary design through operation, is fundamental to ensure that organic compounds of terrestrial origin, or self-induced by the spacecraft, are controlled to ensure successful completion of science objectives.

This paper examines contamination control challenges specific to landed missions (which include sample acquisition, encapsulation, caching, potential sample return, and instruments), and orbiting missions (modeling interactions between the spacecraft and local exospheres and plumes).

2. Mission specific challenges

Contamination Control planning and implementation is mission specific and unique for each space exploration mission. The development of a contamination control program for a space exploration mission targeting detection of organic compounds or for potential sample return is significantly more complex than typical commercial spacecraft projects. This paper illustrates challenges being addressed for the upcoming Mars 2020 and Europa Clipper missions.

2.1 Mars 2020 Mission

The Mars 2020 mission is part of NASA's Mars Exploration Program, a long-term effort of robotic exploration of the Red Planet. Mars 2020 leverages the proven design and technology developed for the 2011 Mars Science Laboratory (MSL) mission and rover (Curiosity) that arrived at Mars in August 2012.

The Mars 2020 rover (Fig. 1) has new complement of instruments supporting new science objectives and human exploration measurement goals. The Mars 2020 rover will acquire, encapsulate, and cache individual scientifically selected samples of Martian material for possible return to Earth by a future mission.

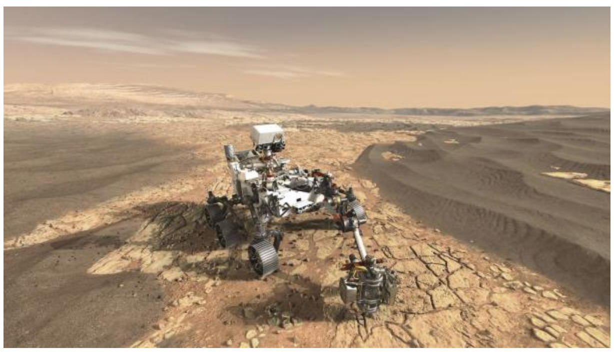

Fig. 1. Mars 2020 Rover artist’s concept

3. Contamination control challenges for sample acquisition, encapsulation and caching

Contamination control is critical to ensure low levels of contamination during sample acquisition, encapsulation and caching for potential return to Earth. The design of the sample collection system must be effective in minimizing and limiting the accumulation of contaminants prior to sample collection.

The Mars 2020 rover will be the first mission intended to collect scientifically selected samples from the surface of Mars for potential return to Earth. The Adaptive Caching Assembly (ACA, shown in Fig. 2) within the body of the rover will be the subsystem responsible for acquiring and storing cylindrical sections of rock, or core samples, from the Martian surface. The corer in the robotic arm will be used for acquisition of Martin samples.

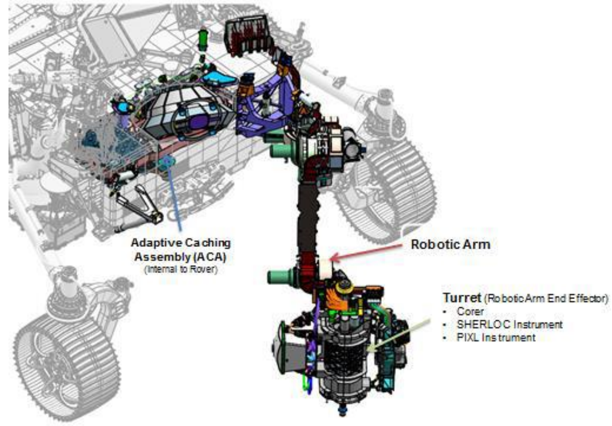

Fig. 2. Mars 2020 Adaptive Caching Assembly (ACA), robotic arm and turret

The samples will be individually encapsulated and sealed in sample tubes in the Tube Sealing and Drop Off Station (shown in Fig. 3).

The sample acquisition process occurs in a precise sequence, with the ACA working in conjunction with the rotary percussive drill. A sample tube is extracted and inserted into a hollow drill bit. As the rotary percussive corer drills into the Martian surface, the core sample is forced into the clean sample tube. The process is complete with the sealing of the sample tube.

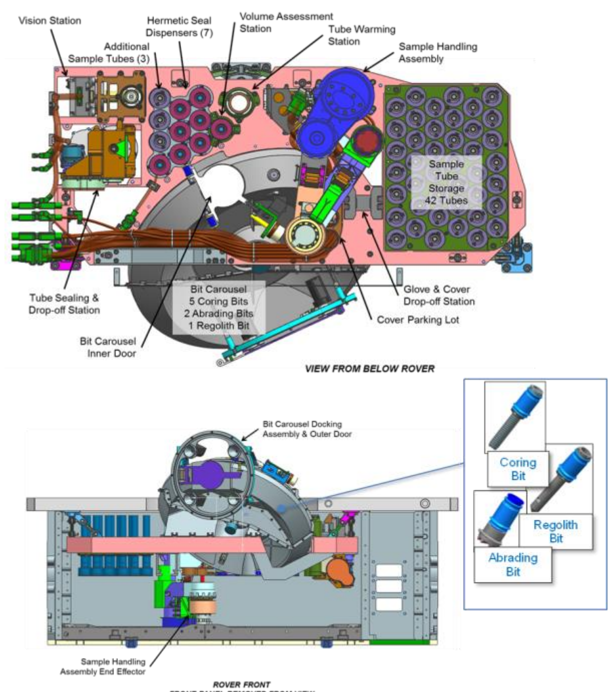

Fig. 3. Mars 2020 Adaptive Caching Assembly detail

Several methods were used to achieve the low levels of contamination required by this mission:

- Selection of low outgassing materials

- Reduction of outgassing rates through extensive vacuum baking
- Use of preferential venting schemes to divert molecular effluents from outgassing
- Use of molecular adsorber coatings within sample caching systems
- Use of Low Surface Energy (LSE) coatings (TiN) on Low Surface Roughness (LSR) materials to minimize molecular deposition
- Use of a Fluid Mechanical Particle Barrier (FMPB) in the sample tubes [2]

3.1 Selection of low outgassing materials

Selection of materials exhibiting low outgassing rates simplifies processing, reducing the duration of vacuum baking operations.

While ASTM E595 [3] can be useful in screening for Total Mass Loss (TML) and Collected Volatile Condensable Materials (CVCM), characterization of outgassing rates through ASTM E1559 is critical for application to contamination sensitive missions.

The ASTM E1559 test method B allows for custom test parameters that are tailored to mission specific applications:

- Outgassing source temperature selection within the operating temperature of the material
- Thermoelectric Quartz Crystal Microbalance (TQCM) receive temperature simulating operating temperatures of contamination sensitive hardware of interest
- Sufficiently long test duration to support development of outgassing rate decay models
- QCM Thermo-Gravimetric Analysis (QTGA) of collected contaminant deposit
- Mass spectrometer data collection during the test for identification of molecular effluent composition

One of the major materials selection challenges for the Mars 2020 mission was in the selection of suitable materials for the sample collecting hardware that meet the strict inorganic and organic contamination limits.

This required limitations on the levels of approximately 20 elements (e.g., tungsten, sulfur) that are critical for the scientific study of cached samples.

Further, organic contaminants were assessed on the basis of total organic carbon and imposed limits on critical "Tier 1" organic compounds.

3.2 Reduction of outgassing rates through vacuum baking

Vacuum baking non-metallic materials at the lowest levels of assembly is an effective technique to reduce outgassing rates to the required levels.

Monitoring of the vacuum bakeouts with QCMs until QCM deposition exit criteria are achieved is the most effective way to verify that molecular outgassing is controlled to the required levels. However, vacuum chamber background levels need to be verified to ensure that exit criteria requirements can be met.

For Mars 2020, verifying outgassing rates down to the required levels, at stringent temperature limits presents a challenge, as vacuum chambers with sufficiently low background levels are not widely available.

3.3 Use of preferential venting schemes to divert molecular effluents from outgassing

Enclosed sources, such as electronic boxes containing conformal-coated electronic boards and cabling, are significant sources of outgassing, even after these assemblies are vacuum baked. Designing outgassing venting paths to redirect molecular outgassing effluents to areas with low sensitivity to contamination is effective in controlling contamination in sensitive systems.

3.4 Use of molecular adsorber coatings within sample caching systems

Molecular adsorbers can be incorporated in the design to minimize contamination to sensitive surfaces by collecting molecular effluents.

For Mars 2020, the desired selection criteria for molecular adsorber were:

- Hydrophobic properties to prevent molecular loading during Assembly, Test and Launch Operations (ATLO)
- Ability to adsorb organic outgassing products (higher molecular weight) while exposed to vacuum during the long-duration cruise
- Ability to absorb organic outgassing products in the Martian environment, without loading under the carbon dioxide atmosphere

Tenax (Buchem B.V., The Netherlands), a porous polymer resin based on 2,6-diphenyl-pphenylene oxide was evaluated, and ultimately selected, as an absorber to protect the Mars 2020 adaptive caching assembly (ACA) from outgassed molecular contamination. Tenax is a well-documented absorber extensively used in analytical chemistry. Tenax absorbs compounds relevant to spacecraft and flown on spacecraft to trap organics for chemical analysis. [5-11]

One of the application concerns that was addressed through a test program were the fabrication, mounting and mechanical stability (particle shedding) during launch.

3.5 Use of Low Surface Energy (LSE) coatings to minimize molecular deposition

Use of Low Surface Energy (LSE) coatings on Low Surface Roughness (LSR) materials is an effective way to minimize accumulation of contaminants on sensitive surfaces.

Gold is a commonly selected low surface energy coating. However, titanium nitride was selected for application in the Mars 2020 sample tubes.

3.6 Use of a Fluid Mechanical Particle Barrier (FMPB) in the sample tubes

For Mars 2020, contamination of the sample tubes will also be prevented through the design a physical barrier called the Fluid Mechanical Particle Barrier (FMPB), [2] a cylindrical enclosure surrounding each tube. The FMPB takes advantage of fluid viscosity to slow down the speed of the flow through a thin annular orifice at the bottom of the device.

For the flow speeds expected at the various phases of the Mars 2020 mission, no penetration of particles >5 μm is expected inside the orifice. Large margins on the already low contamination probability of the tubes are allowed by the presence of a large-volume cavity immediately downstream of the annular orifice. The cavity minimizes particle penetration even at the most extreme conditions expected on Mars.

3.7 Particle resuspension modeling

When subjected to wind on Mars, particles on the rover can be re-suspended and transported to the Martian surface. The particles may carry organic compounds and terrestrial organisms which may contaminate Martian soil samples.

JPL has developed models to predict the resuspension of particles due to G-forces and wind shear. Experiments were performed to determine model parameters for real-life particles and spacecraft substrates.

An experimental set-up using a laminar flow cell is being used to generate a fully developed laminar flow in a rectangular channel (a phenomenon well characterized by theory). Particles are deposited onto slides and installed in the flow cell. The flow cell is contained in a purge box to control humidity (which affects particle removal rates). Microscope images are taken the particle removal fraction at various flow rates.

The JPL model, supported by extensive experimental data, is applied to characterize particle resuspension and transport under a wide range of Martian wind conditions (Fig. 4).

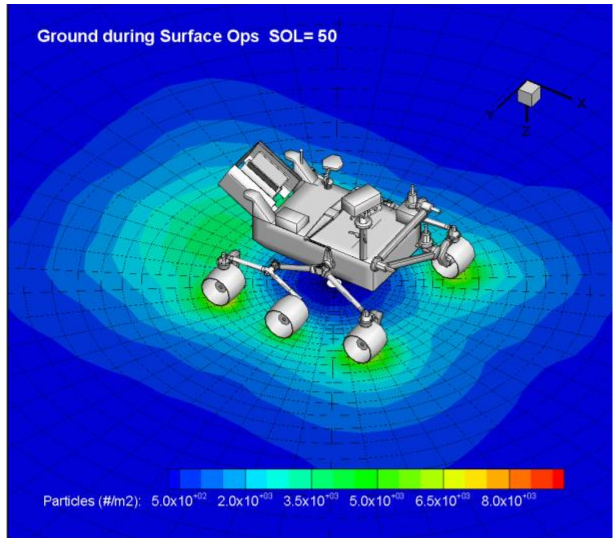

Fig. 4. Illustration of particle resuspension and transport for the Mars 2020 rover on the surface of Mars

4. Challenges for Potential Sample Return

Achieving low levels of contamination on sample acquisition and collection systems is a significant challenge, and also critical to mission success.

The contamination limits, based on the NASA Organic Contamination Panel (OCP) science recommendations, [1] for potential return of rock core samples present a significant contamination control challenge.

Given the low levels of these limits, it is challenging to carry out quantitative analysis that can verify with high confidence that the hardware meets these surface cleanliness requirements.

5. Contamination control challenges for UV instruments: UV Raman spectroscopy and fluorescence

Deep UV (DUV) resonance Raman and fluorescence spectrometers are highly sensitive to contamination and the successful science function of these instruments is dependent on contamination mitigation.

The Mars 2020 SHERLOC is an instrument with unprecedented levels of sensitivity to condensed carbon and aromatic organics. SHERLOC analysis of the fluorescence spectra identifies number of aromatic rings present, and identifies regions of high organic content. Contamination control is critical to prevent condensation of contaminants on optical surfaces, and eliminate contaminants that would fluoresce in the UV. Part of the contamination mitigation methods include careful material selection, testing of all selected materials, and processing/vacuum baking materials to reduce outgassing.

Contamination induced transmission loss due to attenuation is a significant source of performance degradation for UV instruments. Figure 5 illustrates this attenuation.

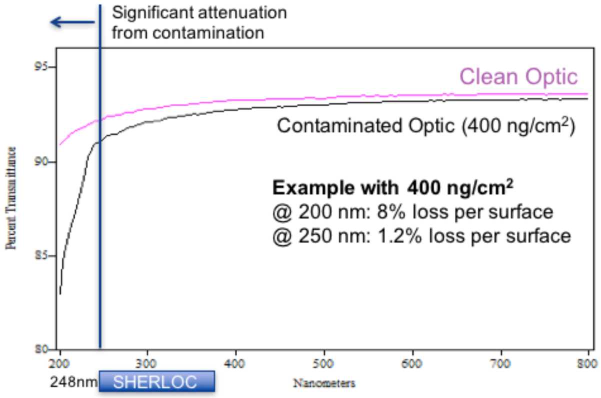

Fig. 5. Contamination induced attenuation on clean and contaminated optics

The following factors must be considered in determining acceptable contamination levels:

- Attenuation (laser, optics in the illumination path and the collected light)
- Fluorescence/Raman effect from sources of material outgassing
- Collection efficiency into the spectrometer

Fluorescence of contaminant deposits can mask the Raman spectral response

Additional materials testing is necessary to evaluate the effect of outgassed condensate to the UV instrument optics

6. Modeling interactions between spacecraft molecular emissions with local exospheres and plumes

For the Europa Clipper mission (depicted in Fig. 6), a mass spectrometer will measure the composition of the exospheric components. The exosphere is composed of molecular effluents produced by sublimation of the surface. The density is further enhanced over sunlight regions and presents a target for measurements. The exosphere [12-13] also includes particles sputtered from the surface by the bombardment by high-energy particles, and ejected surface particles in plumes and particles sputtered from the surface.

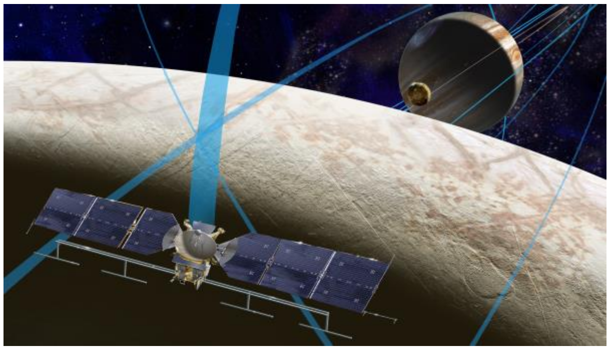

Fig. 6. Europa Clipper artist's concept

One of the Europa Clipper instruments is a next-generation spectrometer with significantly improved capabilities when compared to existing instruments. Performance enhancements include:

- Extended mass range for heavy organic molecules
- Enhanced mass resolution for critical isotopes
- Enhanced dynamic range for high signal-to-noise ratios
- Improved sensitivity for rare noble gases
- High throughput for rapid descent probes

During Europa orbital passes, when the spectrometer will be making measurements, molecular emissions from the spacecraft (from materials outgassing and thruster operations) will interact with the local exosphere. The spacecraft induced molecular effluents will collide with molecules from the ambient exosphere and a fraction of the spacecraft emissions are returned to the spacecraft. The rate at which the emitted molecules are returned to the spacecraft by collisions with other molecules (in Europa's exosphere) is known as the return flux.

Return flux of molecular emissions from spacecraft sources contribute to contaminant deposition onto the complement of contamination sensitive instruments. Characterization of return flux is critical to the definition of requirements for materials outgassing (for the spacecraft and instruments) and for the definition of thruster operations.

7. Conclusions

This paper describes significant contamination control challenges associated with detection of organic compounds, and sample acquisition for potential return to Earth. Mission specific challenges being addressed by the Mars 2020 and Europa Clipper missions are used to illustrate the unique character of contamination control activities supporting these missions.

The challenges illustrate the multidisciplinary aspect of contamination control engineering for space exploration missions, and the diversity of problems associated with detection of organic compounds, and sample acquisition for potential return to Earth.

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